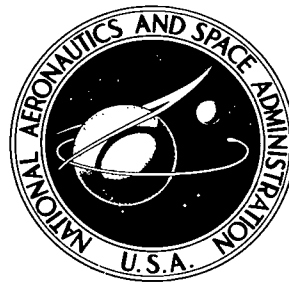


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A PRELIMINARY INVESTIGATION OF PROJECTILE SHAPE EFFECTS IN HYPERVELOCITY IMPACT OF A DOUBLE-SHEET STRUCTURE

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SUMMARY

Impact tests of a sphere and several cylinders of various masses and fineness ratios, all of aluminum, fired into an aluminum double-sheet structure at velocities near 7 km/sec, show that a cylinder, impacting in the direction of its axis, is considerably more effective as a penetrator than a sphere. Impacts of three cylinders of equal mass, but different fineness ratios ($1/2$, 1 , and $3/2$), produced holes through the structure's rear sheet, whereas impact of a sphere of the same mass did not. Moreover, it was found that to prevent rear-sheet penetration, the mass of the $1/2$ -fineness-ratio cylinder had to be reduced by a factor greater than three. Further tests wherein the cylinder diameter was held constant while the cylinder length was systematically reduced showed that a cylinder with a fineness ratio of 0.07 and a mass of only $1/7$ that of the sphere was still capable of producing a hole in the rear sheet.

INTRODUCTION

Future space missions involving flights of large space vehicles for long periods of time will be subject to impact with meteoroids. This hazard makes it necessary to consider the use of spacecraft structures that will provide protection.

The most effective structure yet found for resisting meteoroid impact is the double-sheet structure, which consists of two sheets spaced some distance apart. The front sheet serves as a "meteor bumper" while the rear sheet acts as the pressure-sustaining hull of the spacecraft. A meteoroid impact with the bumper fragments and partially melts both the meteoroid and a portion of the bumper material, causing a debris of small individual particles to be sprayed over a large area of the hull. The penetration effectiveness of these lower energy particles, dispersed over a large area, is thus very much reduced.

The meteor-bumper concept for protecting spacecraft from impact was first suggested by Whipple in 1947 (ref. 1). Many investigators have since impacted double-sheet structures with hypervelocity projectiles to determine experimentally the effects of several variables on structure performance (see, e.g., refs. 2-9). The variables investigated include the size and density of the projectile, the thicknesses of and the spacing between the two sheets comprising the structure, the velocity of the projectile at impact, and the angle between the flight path and the surface of the structure.

The effects of projectile shape, however, have received little attention because only spherical projectiles were used in most of the tests. Since these effects are relatively unknown, the amount of protection afforded by double-sheet structures against irregularly shaped meteoroids must be investigated. The present study investigated the effect of cylindrical projectiles on double-sheet structures. Tests were conducted with cylindrical projectiles of various masses and fineness ratios, and the results compared with the damage caused by a spherical projectile.

EXPERIMENTAL PROCEDURE

The investigation was conducted in two parts. The object of the first part was to determine whether a sphere or a cylinder was the more effective penetrator. To do this, a double-sheet structure was impacted by a 3.96-mm-diameter sphere and three cylinders of equal mass but of different fineness ratio (ratio of length to diameter). Three fineness ratios (1, 1/2, and 3/2) were chosen to show that the damaging capability of the cylinder was not peculiar to a particular one. The object of the second part was to provide a measure of the penetration effectiveness of the cylinder relative to that of the sphere. To do this, the structure was impacted by cylinders of various masses first with fineness ratio held constant, then with cylinder diameter held constant.

The sphere and cylinders were 2017-T4 and 2024-T351 aluminum, respectively. They were sabot mounted and launched at velocities near 7 km/sec from the light-gas guns (refs. 9 and 10). Each gun had a rifled barrel that imparted spin to the projectiles to ensure separation of the sabot segments and to maintain a low angle of attack, not exceeding 5°, for each cylinder.

Both sheets of the double-sheet structure (each measuring 15.2 × 15.2 cm) were 2024-T3 aluminum, spaced 5.40 cm apart. The front and rear sheets were 1.0 and 2.0 mm thick, respectively. The front sheet thickness was one-fourth the sphere diameter so that a large portion of the spray debris material would melt (ref. 8), whereas the rear sheet was just sufficiently thick to prevent penetration by the spray debris when impacted by the sphere.

During each test, the impacting projectile and the debris sprayed from the front sheet were photographed in silhouette by a motion picture camera at approximately one million frames per second. From the pictures it was possible to determine, to within 5 percent, the velocity of the spray-debris front relative to that of the projectile before impact.

DISCUSSION OF RESULTS

The experimental data obtained in the tests are given in table 1.

Impact Tests of Equal-Mass Projectiles

The results of the first part of the investigation are given in figure 1. In each case, the spray-debris has damaged the rear sheet over a large area on the front surface and a much smaller area

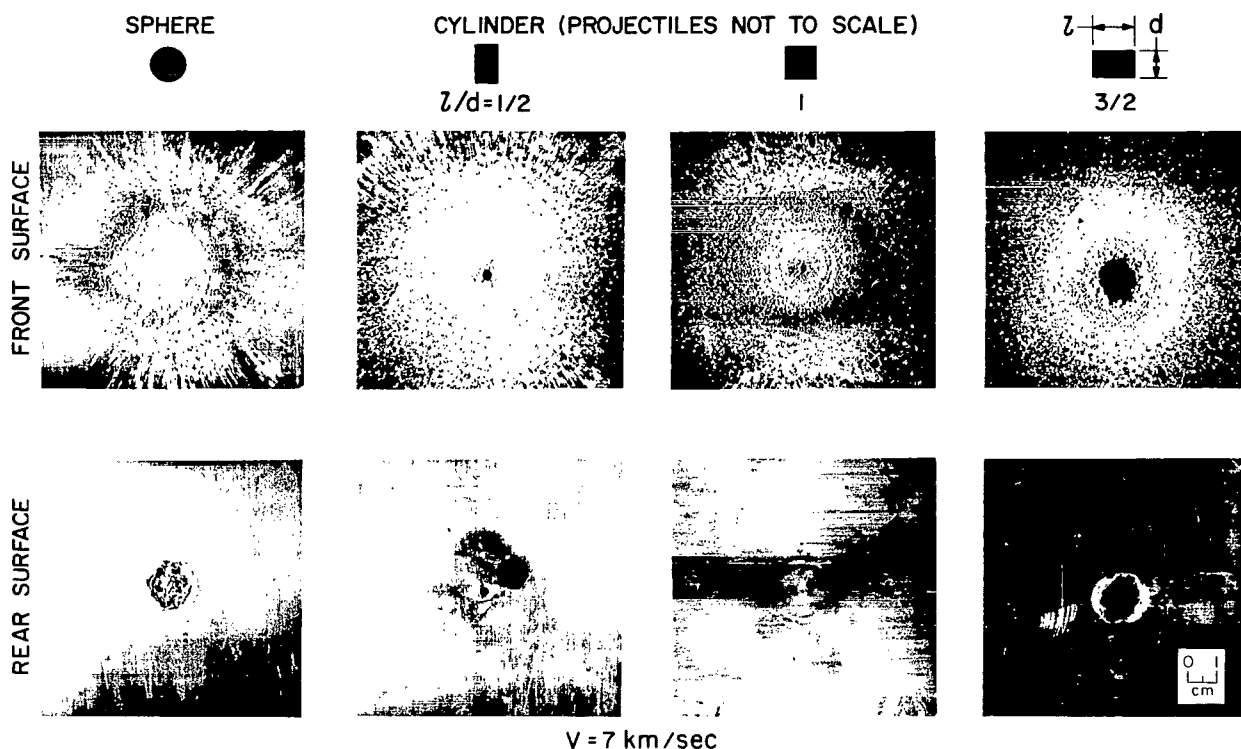


Figure 1. -- Damage caused to front and rear surfaces of rear sheet by impacts of projectiles of equal mass; $m = 0.09$ g.

on the rear surface. The spray-debris for each cylinder produced a hole, whereas that for the sphere did not. Instead, the spray-debris for the sphere caused only spallation of the rear surface. The rear sheet in this case was not penetrated and could therefore still sustain a pressure differential of 1 atmosphere.

The average diameter of the hole produced in the rear sheet by each cylinder impact is listed in table 1. The hole diameter is largest for the cylinder of $3/2$ fineness ratio probably because fragmentation of the rear portion of the cylinder was incomplete causing impact on the rear sheet of relatively large spray-debris particles having only small angular divergence. Evidence for this is provided by figure 1, which shows relatively large pits, or craters, on the rear sheet's front surface, near the periphery of the hole. The least damage to the rear sheet was caused by the cylinder of fineness-ratio 1. Why this cylinder produced a smaller hole than the $1/2$ fineness-ratio cylinder is not clear.

The reason for the greater penetration effectiveness of the cylinders becomes evident on examination of figure 2. This figure shows for each impacting projectile a high-speed movie frame of the spray-debris just before impingement on the rear sheet.¹ The greater penetration

¹A photograph of the test firing of the sphere is not available. However, a picture is included of the spray for the impact of a sphere at the same test velocity, on a similar structure having the same front-sheet thickness but with a larger spacing between sheets. The rear sheet in this case is outside the field of view of the picture.

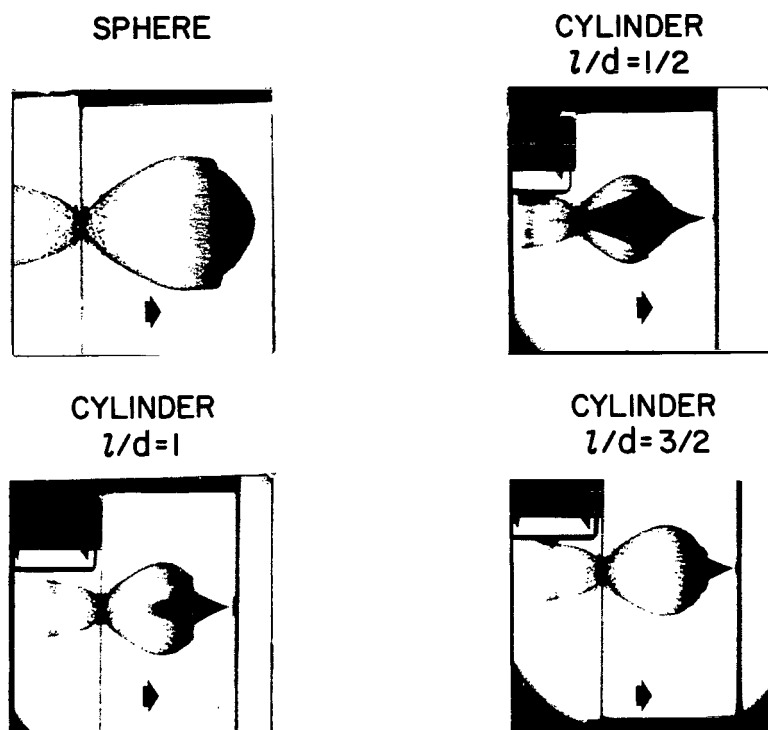


Figure 2. — Debris sprayed from front sheet by impacts of projectiles of equal mass; $m = 0.09$ g, $V = 7$ km/sec.

effectiveness of the cylinders is due to (1) the spray-debris material for each cylinder impact being concentrated near the flight axis as a “spike,” in contrast to the diverging bubble of spray-debris for the sphere, and (2) the spray-debris front for each cylinder impact moving an average of 14 percent faster than that for the sphere (see table 1). Both phenomena result from a difference in the shape of the shock waves reaching the rear surface of the front sheet. For the cylindrical projectiles, the shock near the axis is planar, whereas for the sphere the shock is more nearly hemispherical.

Impact Tests of Cylinders of Various Masses

The last part of the investigation consisted of two test series in which the cylinder mass was reduced, in two different ways, to determine the minimum mass that would still penetrate the rear sheet. In the first test series, the cylinder mass was reduced by holding the cylinder fineness ratio at $1/2$ while decreasing the cylinder size; in the last test series, the cylinder mass was reduced by holding the cylinder diameter at 4.4 mm while the cylinder length systematically decreased.

The results of the first test series, with the $1/2$ -fineness-ratio cylinders, are given in figures 3 and 4. Figure 3 shows the rear-sheet damage for each impact, and figure 4 presents a plot of the average rear-sheet hole diameter versus the ratio of the mass of the cylinder to that of the sphere.

1/2 FINENESS RATIO CYLINDERS (NOT TO SCALE)

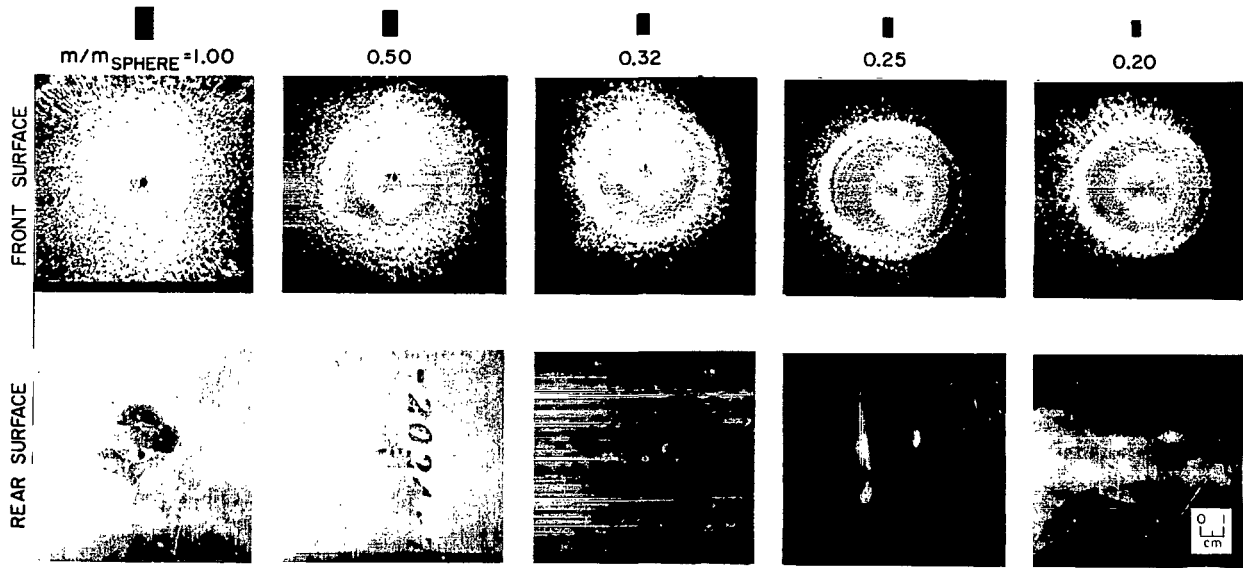


Figure 3. — Damage caused to front and rear surfaces of rear sheet by impacts of cylinders of 1/2 fineness ratio; $V = 7$ km/sec.

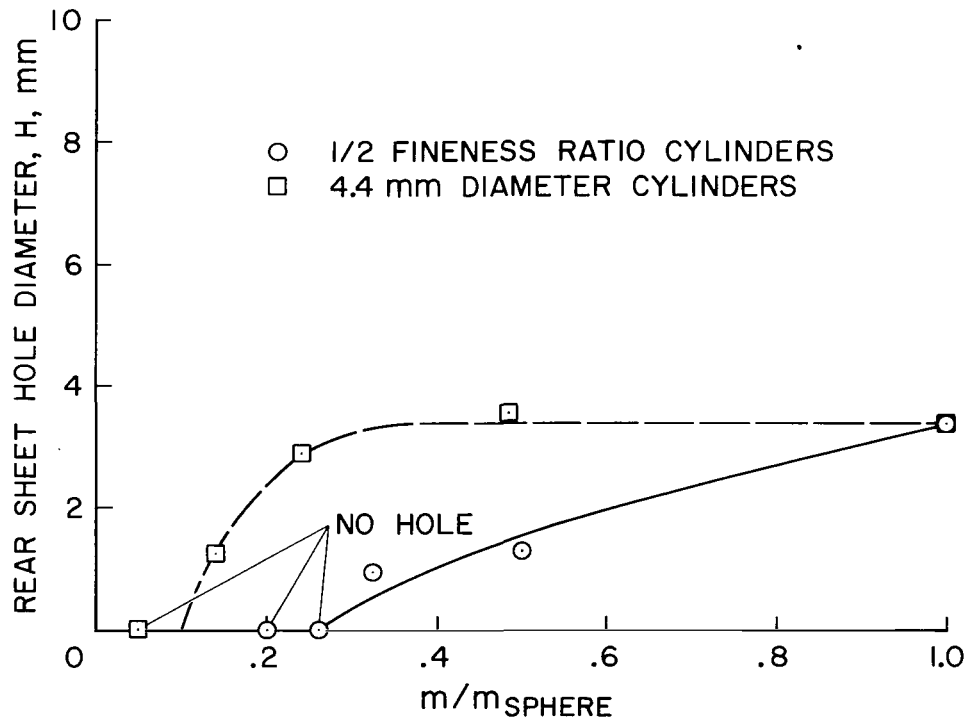


Figure 4. — Rear-sheet hole diameter versus ratio of cylinder mass to sphere mass.

The two figures show that the 1/2-fineness-ratio cylinders continued to produce holes down to one-third the sphere's mass. At one-fourth the sphere's mass, however, no hole was produced and the rear surface was only dented.

The spray debris corresponding to the impact of each 1/2-fineness-ratio cylinder is shown in figure 5. In each case, the spray-debris front was a "spike" with a velocity 6 percent greater on the average (see table 1), than that of the cylinder before impact. The magnitude of this velocity indicates that the portion of the shock wave near the axis reached the rear surface of the front sheet without being attenuated by rarefaction waves, even in the case of the smallest cylinder, and further, that the shock wave there was still planar. As the cylinder diameter decreases, however, the diameter of the planar portion of the shock wave at the rear surface of the front sheet decreases accordingly. This smaller planar-shock diameter and the reduced cylinder mass result in less spray-debris material being concentrated near the axis. This smaller concentration of material, rather than a reduction in the velocity of the spray-debris front, is therefore responsible for the failure of the smallest two cylinders of this test series to penetrate the rear sheet.

The results of the last test series, with the 4.4-mm-diameter cylinders, are given in figure 6. which shows the rear-sheet damage for each impact. This figure and figure 4 show that the constant-diameter cylinders of mass greater than 1/7 that of the sphere produced holes. At 1/20 of that mass, the rear surface was only dented. Therefore, the minimum mass required to penetrate the rear sheet in this case is much less than that required for the 1/2-fineness-ratio cylinders of the previous test series. Moreover, a hole produced by a cylinder with lower fineness ratio, but greater diameter, was larger than that produced by a 1/2-fineness-ratio cylinder of the same mass.

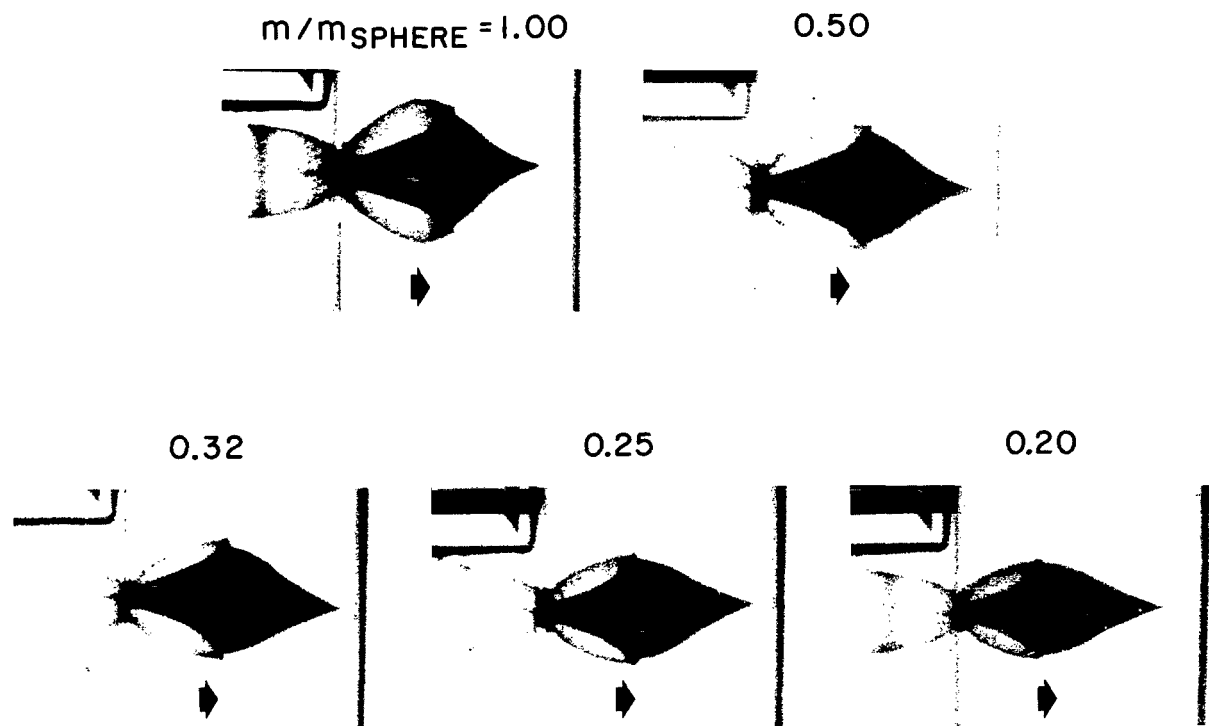


Figure 5. — Debris sprayed from front sheet by impacts of cylinders of 1/2 fineness ratio.

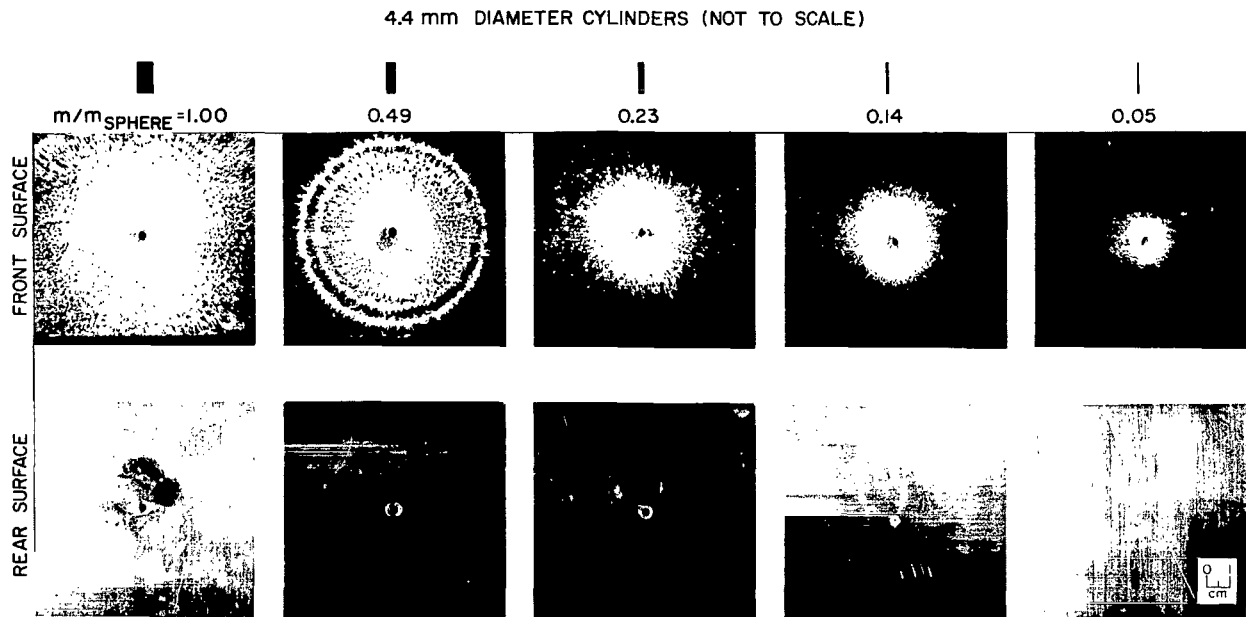


Figure 6. — Damage caused to front and rear surfaces of rear sheet by impacts of 4.4-mm-diameter cylinders; $V = 7$ km/sec.

The spray-debris pattern corresponding to the impact of each constant diameter cylinder is shown in figure 7. In each case, the spray-debris front is again a spike, with a velocity that is (except for the impact of the shortest cylinder) on the average 9 percent greater than that of the cylinder before impact. This debris velocity, although slightly higher, is not significantly different from that measured for the cylinder impacts of the previous tests. For the impact of the shortest cylinder, however, the velocity of the spray-debris front was only 66 percent of the cylinder's velocity. This much smaller velocity, together with a reduced concentration of spray-debris material at the axis, resulting from a reduction in cylinder mass, accounts for the failure of the spray debris for the shortest cylinder to penetrate the rear sheet. This smaller velocity results from attenuation of the shock wave on the axis before it reaches the rear surface of the front sheet. Calculations of the wave speeds indicate that the initial attenuation of the shock wave on the axis occurs in this case not as a result of the shock wave being overtaken by radial rarefaction waves, but by the axial rarefaction wave, which originates from the projectile's rear surface. (A discussion of the shock and rarefaction waves generated in a cylindrical projectile and a target as a result of impact and a method for calculating their speeds is given in ref. 11.)

In past studies on impact in double-sheet structures the importance of projectile shape was not generally recognized and the sphere was commonly accepted as a convenient standard projectile shape for simulating meteoroids. The results of this investigation, however, show that at the impact speeds of this test, a cylinder, impacting in the direction of its axis, is considerably more effective as a penetrator than as a sphere of equal mass and that the effects of projectile shape are therefore very significant. Thus the use of only spherical projectiles in testing double-sheet structures can be misleading. In fact, this practice has yielded nonconservative empirical equations, now in use in the design of impact-resistant spacecraft structures. Although cylinders are no more typical of

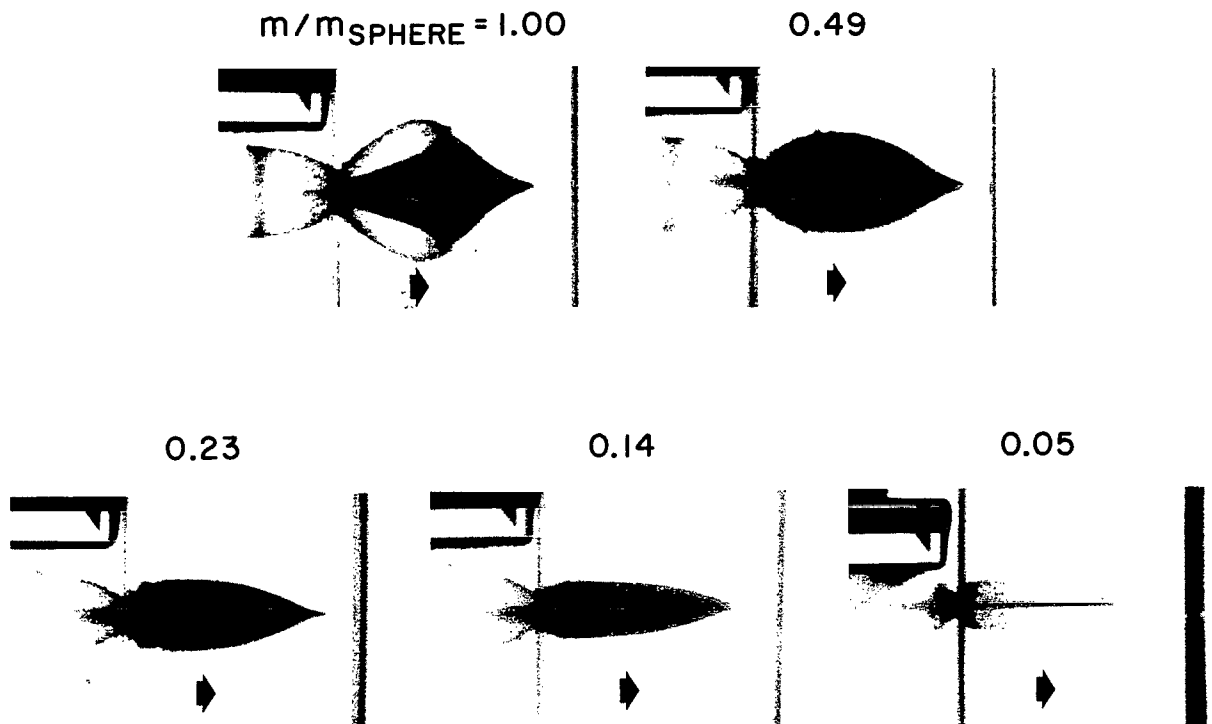


Figure 7. — Debris sprayed from front sheet by impacts of 4.4-mm-diameter cylinders.

meteoroid shapes than spheres, the damage incurred by actual meteoroids is undoubtedly being underestimated by a significant factor. Therefore, a more complete investigation of projectile shape effects on double-sheet structure performance is warranted and should include tests with projectiles of other shapes, perhaps prolate and oblate spheroids and possibly even irregularly shaped projectiles.

CONCLUDING REMARKS

The results of this study support the conclusion that typical empirical equations now in use for the design of spacecraft structures resistant to meteoroid impact are nonconservative because they are based solely on spherical-projectile data and do not consider the effects of meteoroid shape.

As a penetrator of a double-sheet structure, a cylinder impacting in the direction of its axis is considerably more effective than a sphere of equal mass; thus the effect of projectile shape on the impact resistance of double-sheet structures is significant. The mass of a cylinder must be reduced to a value much less than that of the sphere to prevent penetration of the structure.

Also, cylinders of low fineness ratio are more effective penetrators of a double-sheet structure than cylinders of higher fineness ratio and of equal mass, at least for the range of fineness ratios from 1/7 to 1/2.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif. 94035, June 1, 1972

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TABLE 1.—SUMMARY OF PERTINENT EXPERIMENTAL DATA

| Round | Projectile | | | | | | | Spray-debris velocity ratio, w/V | Rear-sheet hole diameter, H , mm |
|-----------------------------------|------------|--------------------------|------------------------|-----------------------------|---------------------|-------------------------------|------------------------------|--|---|
| | Shape | Diameter, d , mm | Length, l , mm | Fineness ratio, l/d | Mass, m , g | $\frac{m}{m_{\text{sphere}}}$ | Velocity, V , km/sec | | |
| Equal-mass projectiles | | | | | | | | | |
| SR-246 | Sphere | 3.96 | — | — | 0.0918 | 1.000 | 7.346 | 0.91 | No hole |
| 1537 | Cylinder | 4.36 | 2.20 | 0.505 | .0916 | .998 | 7.013 | 1.04 | 3.56 |
| 1524 | Cylinder | 3.46 | 3.48 | .994 | .0892 | .972 | 6.802 | 1.06 | 1.3 |
| 1517 | Cylinder | 3.02 | 4.55 | 1.51 | .0890 | .969 | 6.530 | 1.02 | 15.5 |
| Constant-fineness-ratio cylinders | | | | | | | | | |
| 1521 | Cylinder | 3.47 | 1.77 | 0.510 | 0.0461 | 0.502 | 7.113 | 1.05 | 1.3 |
| 1528 | Cylinder | 3.01 | 1.53 | .508 | .0293 | .319 | 7.376 | 1.05 | .96 |
| 1530 | Cylinder | 2.76 | 1.38 | .500 | .0231 | .252 | 7.244 | 1.05 | No hole |
| 1529 | Cylinder | 2.57 | 1.28 | .498 | .0182 | .198 | 7.237 | 1.09 | No hole |
| Constant-diameter cylinders | | | | | | | | | |
| 1536 | Cylinder | 4.39 | 1.10 | 0.250 | 0.0446 | 0.486 | 7.273 | 1.13 | 3.73 |
| 1538 | Cylinder | 4.35 | .536 | .123 | .0211 | .230 | 7.136 | 1.12 | 2.92 |
| 1539 | Cylinder | 4.36 | .300 | .0688 | .0124 | .135 | 7.048 | 1.02 | 1.3 |
| 1540 | Cylinder | 4.35 | .11 | .025 | .0043 | .047 | 7.260 | .66 | No hole |



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